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Repulping of Wet Strength Papers Using Chlorine Dioxide and Sodium Borohydride

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Using Chlorine Dioxide and Sodium Borohydride

by

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Abstract

Wet strength papers are papers that retain 15 % of their dry strength. Wet strength agents form non-hydrogen bonds with the cellulose so that the bonds are not broken when saturated with water. When these agents are used repulping of the product becomes very difficult. Therefore, a chemical treatment is necessary to break the bonds and disperse the fibers. Generally speaking a high pH and high temperature are desired to assist in breaking the bonds.

Chlorine dioxide and sodium borohydride were analyzed to determine the best repulping chemical. Success will be measured by several factors. These factors are: least amount of fiber degradation, speed of repulping, and least amount of chemical used.

This experiment was performed using beverage carriers as the wet strength paper. The beverage carriers were repulped in a Tappi disintegrator using chlorine dioxide and sodium borohydride at 1% concentration and 3% concentration levels. Three pulping times of ten, twenty, and thirty minutes, were used for the pulping runs. After the pulping runs were completed a shive count was taken and compared to the control run. Handsheets were made and tested for tear index, tensile index and burst index. A fiber length analysis was also performed to determine the amount of fiber damage.

The results of the testing gave acceptable numbers. The shive analysis showed the three percent sodium borohydride had the best fiber dispersion with one percent sodium borohydride having the second best. The chlorine dioxide failed to show acceptable degrees of fiber dispersion. The strength tests, tensile index, tear index, and burst index, showed that the strongest fibers were those pulped with sodium borohydride, at both concentration levels. The fiber length analysis showed that at thirty minutes the control run had the largest average fiber length. For shorter pulping times the sodium borohydride at both concentrations showed the largest average fiber length.

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Introduction

In recent years there has been a significant trend toward recycling for two reasons. The reduction of waste paper going to the landfills, and to reduce the cost of producing paper. A major source of waste papers are those that contain wet strength agents, and present a problem when trying to recycle. Wet strength papers are those that retain at least 15%, and some could retain as much as 50%, of their dry strength when saturated with water. Wet strength paper is made with wet strength agents. Some wet strength agents include: urea-formaldehyde, melamine-formaldehyde, and polyamide resins. There are two ways to form a wet strength These resins form non-hydrogen bonds with the cellulose, so when they are saturated with water the bonds will not break. Typically when repulping, the paper is added to water and agitated, but when repulping a wet strength paper, chemicals are needed to break the non-hydrogen bonds.

The chemicals that are used to repulp wet strength papers are usually bleaching or pulping chemicals, such as, sodium hypochlorite, hydrogen peroxide, and chlorine. These chemicals are used because of their strong oxidizing or reducing properties. However, the chemicals that are used to repulp have to be carefully chosen in order to not diminish strength properties.

Chlorine dioxide and sodium borohydride both could be used to repulp wet strengths; however, the impact that each chemical has on the fiber is not known. The time it takes for these chemicals to repulp the wet strength is as important as the strength properties of the pulp. The tensile, tear, and burst values of the paper made from the repulped wet strength is important, since the paper needs to be strong enough to carry beverage containers. The impact that each chemical has on wet strength and the fiber strength will be determined by repulping beverage carriers at high and low levels of chemical concentration. The fiber damage and strength damage will be determined by comparing strength properties of the of repulped wet-strength handsheets with the original beverage carriers.

All the data will be compared to a control run. The control run will have the same amounts of pulping time, but there will be no chemical additive. Another control run using sodium hydroxide is necessary for all three lengths of time, because the Borol Solution, which contains the sodium borohydride also contains 40% sodium hydroxide.

Literature Review

Wet strengths are paper that contain 15 percent or more of their dry strength when saturated with water. The need for wet strengths is great, due to the use of paper products in everything today. Some products that use wet strength resins are: paper towel, facial tissue, beer labels, and beverage carriers. A normal hydrogen bond cannot be saturated in water and retain strength because the hydrogen bonds are broken when they come into contact with water. The bond has to be a covalent bond or a crosslinked network of wet strength resin (1).

Beverage carriers are made from the polyamide type wet strength resin. PAE, polyamide epichlorohydrin, is formed by reacting aminopolyamide in epichlorohydrin (2). The reaction must be done very carefully so that excessive cross linking does not occur between the converted groups. If excessive cross linking occurs than the resins ability to bond with cellulose would be harmed (2). These resins are affected in a negative manner when lignin sulphonate is present in the pulp (2). The crosslinking that occurs in the paper prevents the fibers from swelling and defibering in the presence of just water. A solvent is needed to help break these bonds.

Polyamide wet strength resins, which are used in beverage carriers, have to be repulped under specific conditions. The most effective conditions seem to be at a pH of 10 to 11(3). Chlorine and oxidizing salts have been found to reduce the polyamide type wet strengths, but are generally limited to bleached wet strength grades (3). Temperature is also an important factor in repulping wet strengths. Since most pulpers are not pressurized the temperature is limited to 212 degrees Fahrenheit, but higher temperatures help in the repulping of wet strengths. Increased agitation creates more fiber-contact, thus promoting the dispersion of the fibers. The consistency of the pulp slurry also has to be considered. The higher the consistency the more efficient the agitation and chemical additive (3).

Oxidizing agents are effective agents used for repulping wet strengths. Hypochlorite is very effective, but only on bleached pulp. The demand for hypochlorite in the repulping of wet strength paper is very high if the paper has not been bleached (4). The same conditions that promote the polymerization of the resin can also promote the hydrolysis of the resin (5).

Experimental Procedure

This project was carried out by repulping beverage carriers in a Tappi disintegrator at two chemical concentrations for both chlorine dioxide and sodium borohydride. Chlorine dioxide repulping was carried out in a laboratory hood. Consistency was held constant, and temperature was monitored closely so that there was a consistent rise in temperature between chemicals. Repulping time was varied to determine the speed of repulping at three time lengths of 10 minutes, 20 minutes, and 30 minutes. Once the pulp samples were collected handsheets were made with the Noble and Wood Handsheet maker and testing was done. Some alterations were made on the typical handsheet procedure. The tests that were performed are: tensile, tear, and burst. A fiber length analysis was done to determine if any cutting of the fiber had occurred. A shive analysis was also done to determine the degree of repulping that had taken place. The strength property values were compared to the control run sample and the comparison will decide if the chemical is suitable for repulping of wet strengths.

The data that needed to be gathered for each pulping run is: temperature, pulping time, shive count, and fiber analysis. Consistency was held constant.

As mentioned some alterations were made on typical procedures; they are as listed:

Tappi Disintegrator operation - The samples were pulped at four percent consistency. Each run required 85 grams of beverage carrier and 2000 ml of water. Then the pulping was accomplished over time periods of 10, 20, and 30 minutes.

Chlorine Dioxide manufacture- To make a 400 ml batch of ClO_2 water. Dissolve 2.8 g of $NaClO_2$ in 400 ml of deionized water. Titrate 2.5 ml HCl into the solution over a fifteen minute period. The water will turn a yellow-green color. This procedure was carried out under a hood and the solution was kept in an ice bath to keep it in solution. Chlorine Dioxide is unstable above 11 degrees Celsius so the product must be stored at low temperatures.

Noble and Wood Handsheets- The Noble and Wood Handsheets were made so their basis weight was as close to the original beverage carriers 460 gsm. This resulted in a very thick fiber mat when it was removed from the headbox; too thick for conventional pressing without destroying the sheet. To solve this problem the sheet was first placed into a felt and an eight by eight board was placed on the top. The sheet was then vertically pressed with a fifteen pound weight to eliminate the excess water. After the initial dewatering the sheet was passed through the press two times to ensure maximum dewatering.

Paper Testing- The tests performed on the paper samples followed their respective TAPPI standards.

Shive Analysis- The shive analysis was taken by passing a slurry, of known oven dry fiber content, through the six cut screen in the pilot plant. The shives were left in the screen after the exiting water is visibly clear. The shives were then dried and their weight was divided by the original amount of fiber, resulting in a percentage of shives.

Fiber Length analysis- The fiber length analysis was completed using the Kajaani Fiber Length Analyzer in the Microscopy Lab. The accepts from the six cut screen were collected and a sample greater than ten thousand fibers was counted using the fiber analyzer.

Results

The results of this thesis are represented graphically in figures 1-5. The data for the graphs can be found in appendix 1 in tables 1-23. Figure 1 is the data obtained from the shive analysis, this figure plots percent shives versus the pulping time for the various chemicals and their concentrations. Figure 2 is the tear strength analysis, plotting tear index versus the pulping time for the various pulping runs. Figure 3 is the data for tensile index versus the pulping time for the seven pulping runs. In figure 4 the trends can be seen for the burst index versus pulping time. In figure 5 the Kajaani fiber length analysis is plotted against time to show the degree of fiber degradation that has occurred for the various pulping runs.

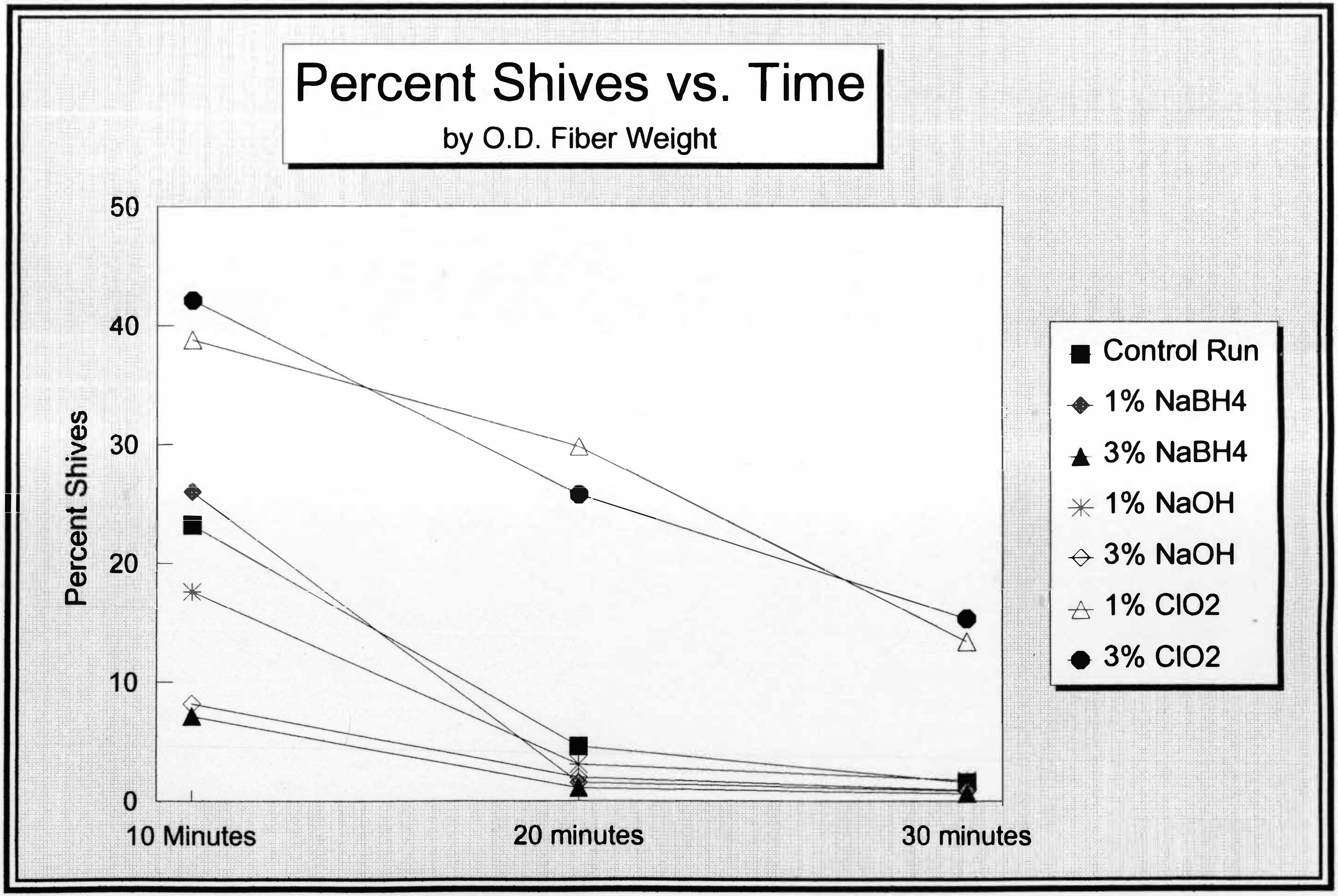
Percent Shives vs. Time
by O.D. Fiber Weight
Percent Shives
50
40
30
20
10
0
10 Minutes
20 minutes
30 minutes
Control Run
1% NaBH4
3% NaBH4
1% NaOH
3% NaOH
1% ClO2
3% ClO2

Figure 1

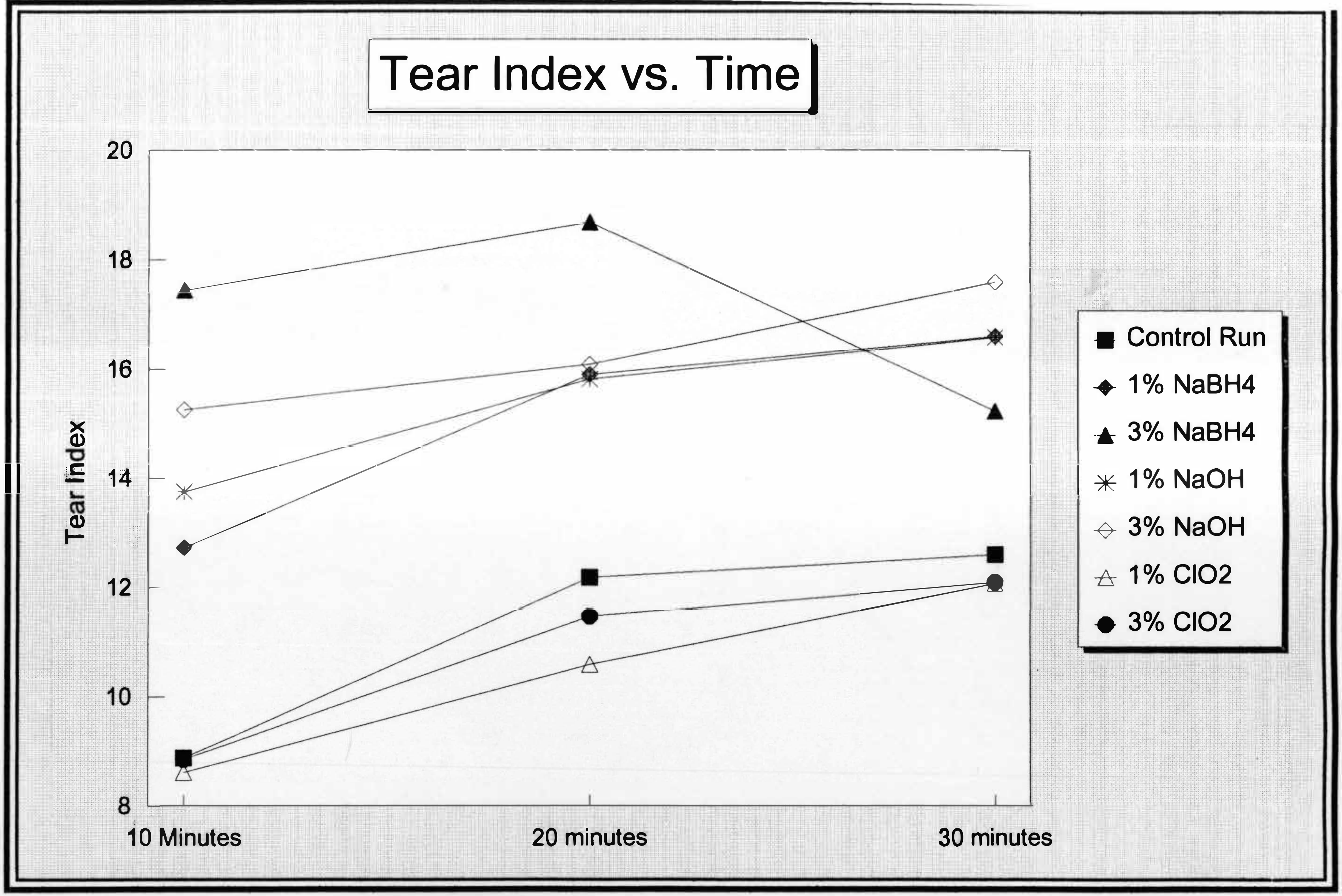
Tear Index vs. Time
Tear Index
20
18
16
14
12
10
8
10 Minutes
20 minutes
30 minutes
Control Run
1% NaBH4
3% NaBH4
1% NaOH
3% NaOH
1% ClO2
3% ClO2

Figure 2

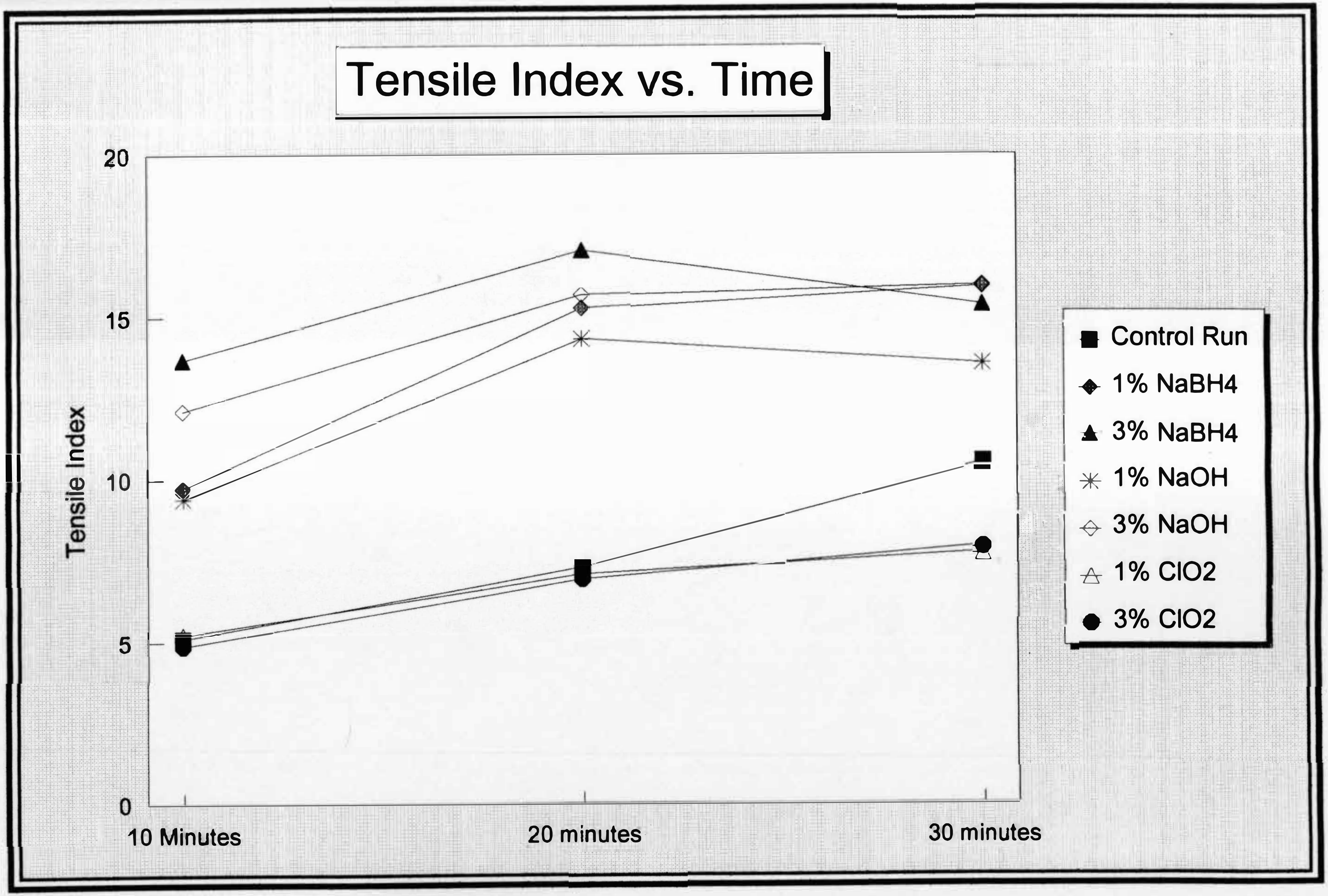
Tensile Index vs. Time
Tensile Index
20
15
10
5
0
10 Minutes
20 minutes
30 minutes
Control Run
1% NaBH4
3% NaBH4
1% NaOH
3% NaOH
1% ClO2
3% ClO2

Figure 3

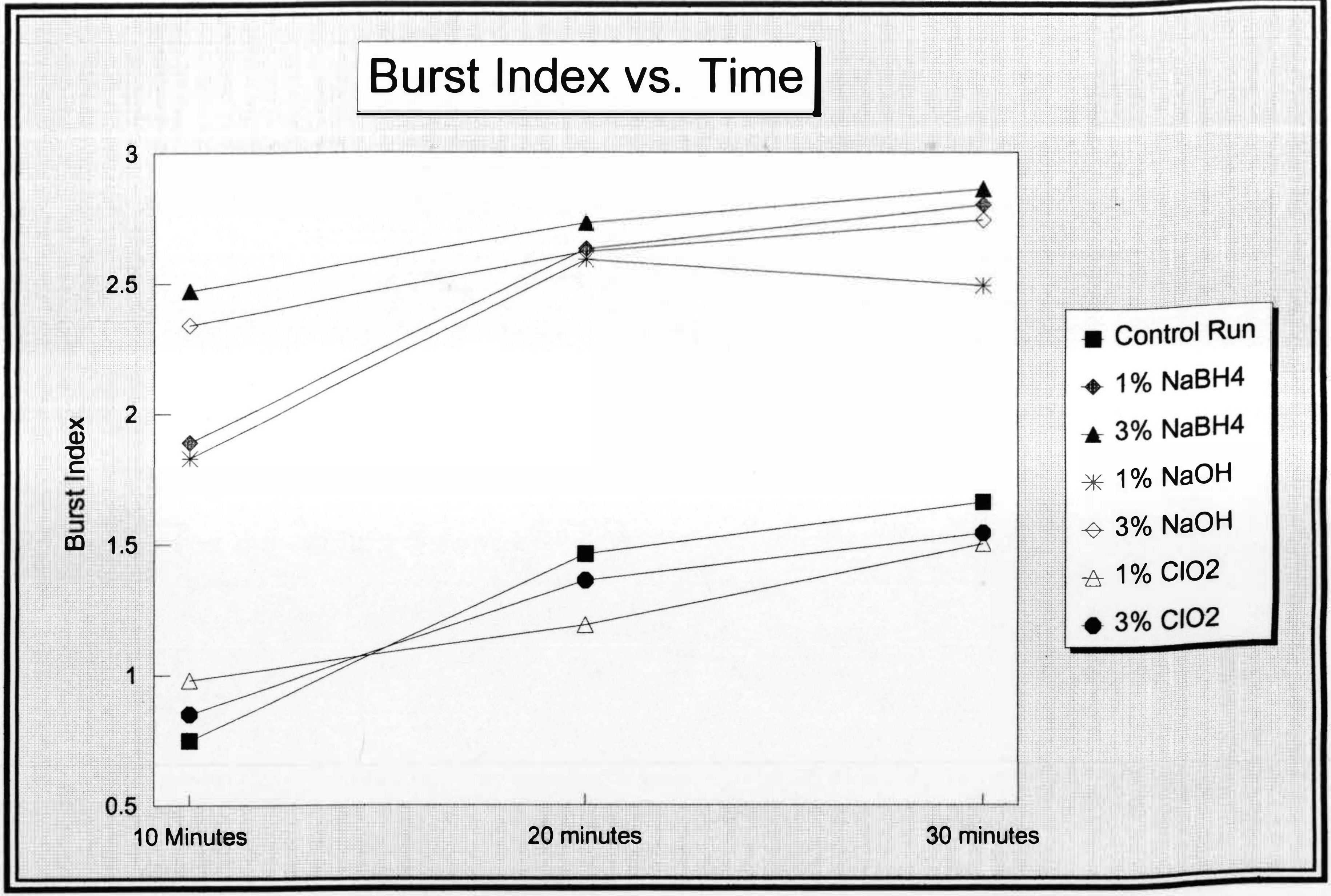
Burst Index vs. Time
Burst Index
3
2.5
2
1.5
1
0.5
10 Minutes
20 minutes
30 minutes
Control Run
1% NaBH4
3% NaBH4
1% NaOH
3% NaOH
1% ClO2
3% ClO2

Figure 4

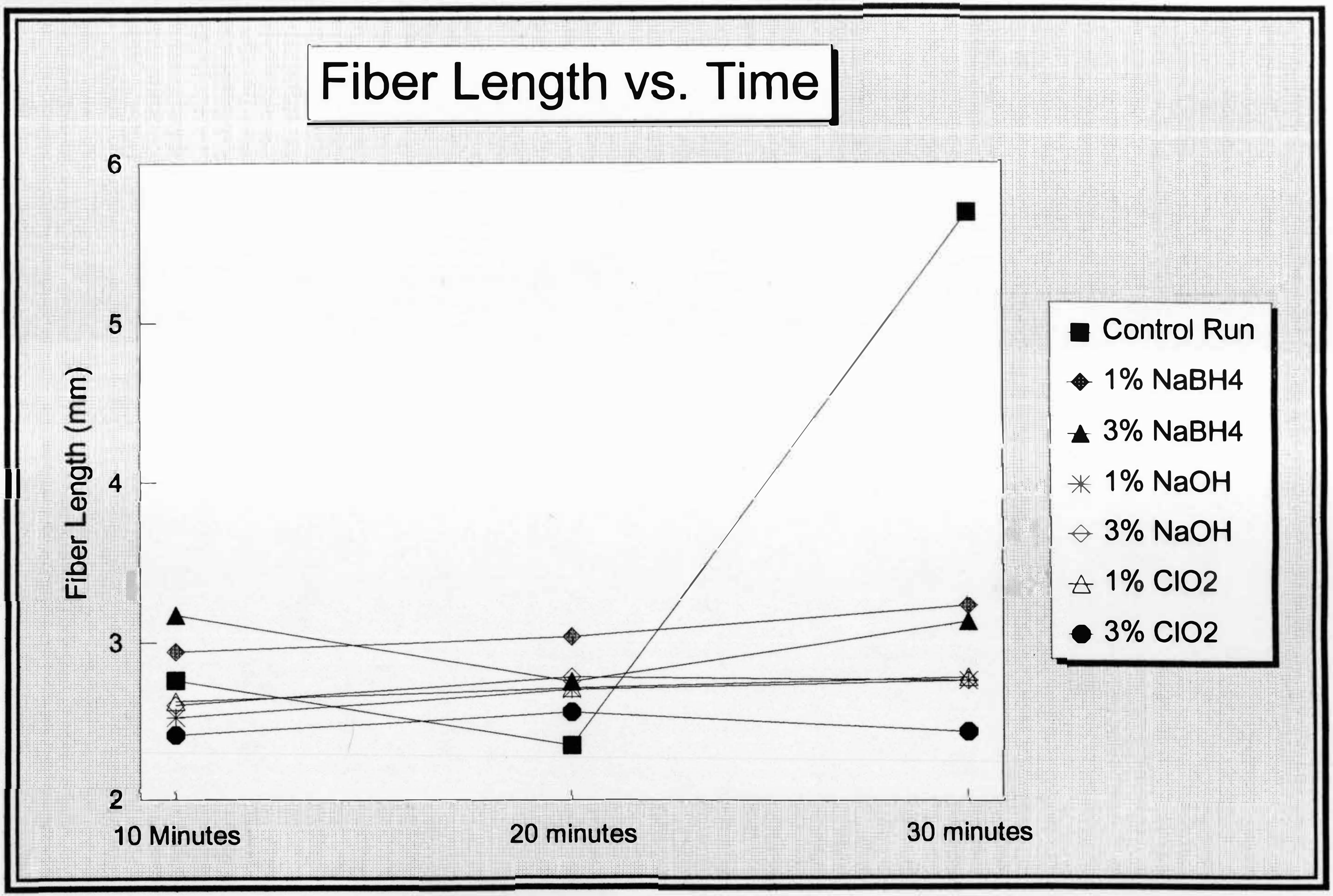
Fiber Length vs. Time
Fiber Length (mm)
6
5
4
3
2
10 Minutes
20 minutes
30 minutes
Control Run
1% NaBH4
3% NaBH4
1% NaOH
3% NaOH
1% ClO2
3% ClO2

Figure 5

Discussion of results

In figure 1 the most obvious and predictable trend that can be seen is the trend of percent shives decreasing with pulping time, which occurs with all of the pulping runs. The pulping runs using chlorine dioxide proved to be very disappointing. Their percent shives were actually higher than that of the control run, which was an unexpected occurrence. The difference between the one percent concentration and the three percent concentration was minimal. There are three explanations for this trend. The first being that the pH of the chlorine dioxide runs were lower than the optimal level for proper fiber dispersion. The optimum pH for fiber dispersion is 10-11, as mentioned earlier in the literature review. The second reason for the unacceptable results was the fact that the beverage carriers being used were unbleached kraft, and the chlorine dioxide was acting on the lignin still left in the pulp. The third reason for these results were the vaporization point of chlorine dioxide. The point vaporization of chlorine dioxide is 11 degrees Celsius, and the temperature of the tap water used was between 10-15 degrees Celsius when measured at the beginning of each run. After 10 minutes of pulping the temperature was recorded in the 22 - 25 degree Celsius range. After 20 minutes the temperatures were being recorded in the 30 - 33 degree range. After the 30 minute pulping time the temperatures were being recorded in the 35 - 39 degree Celsius range. So, the chlorine dioxide would quickly become unstable and go into its gaseous state. For the sodium borohydride the results were much better. The 3% concentration had a significant improvement over the control run and slightly better performance than the sodium hydroxide control run at the ten minute repulping time. The difference between the sodium hydroxide and the sodium borohydride shows that the sodium borohydride has a positive effect on redispersing the fibers. As pulping time increased the level of fiber dispersion was slightly more equal between the concentrations. At the 30 minute pulping time the amount of shives between the two concentrations of the sodium borohydride was minimal.

The strength properties as seen in figures 2 - 4 show the same disappointing results with chlorine dioxide. Chlorine dioxide again showed the worst results of all the runs. However, they were not much worse than the control run. The tear index was significantly lower than the sodium borohydride and sodium hydroxide runs. There was a trend that showed the tear index increasing with pulping time. The same trends were shown for tensile and burst index also. In tensile and burst the data was very close to that of the control run, proving that chlorine dioxide did not harm the fiber, but it did not swell the fiber and allow it to bond any better. The data shown for the sodium borohydride runs and the sodium hydroxide runs show increased strength properties for increased concentration, and for increased pulping time. The reason for the increased strength properties over the control run is because the pH was higher and it allow the fiber to swell quicker and be much more flexible than the untreated fiber and the chlorine dioxide fibers. The more flexible fibers were allowed to be formed and pressed better in the paper making process, resulting in better bonding. Sodium borohydride had slightly better results than the sodium hydroxide at both levels reinforcing the extra potency of the sodium borohydride.

Fiber length data shows the degree of fiber degradation caused by the chemicals. The lowest values again came from the fibers treated with chlorine dioxide, at both concentration levels, with the higher concentration being slightly worse. The longest fiber length was determined to be in the 30 minute run of the control run, but the data may have been prone to error since the length of the fiber is beyond the typical length of a softwood fiber. A comparison can still be made between the other runs. The longest fibers came from the one percent sodium borohydride run, and the three percent sodium borohydride run. The reason for this is the increased ability of fiber swelling. The fibers were swelled and more flexible thus when fiber separation occurred the fibers were seperated more gently than those that were not swelled as in the control run and chlorine dioxide runs. The one percent run for both sodium hydroxide and three percent sodium hydroxide runs resulted in respectable data showing that the swelling potential of the sodium borohydride is slightly better. For the most part the data did not show any severe fiber degradation from any of the runs, and the increased pulping time did not seem to adversely affect the fibers.

Conclusions

The experiment was very successful in showing the potential repulping ability of chlorine dioxide and sodium borohydride. Chlorine dioxide would not be a viable alternative in the redispersion of wet strength papers, for several reasons. The first reason was the pH was too low for efficient dispersion, the chlorine wanted to act on the residual lignin in the unbleached beverage carriers, and the vaporiazation point of chlorine dioxide is too low to withstand the temperatures created by the friction. Another drawback of using chlorine dioxide would be its manufacture for the purpose of repulping wet strengths since it would not be very cost effective. Sodium borohydride would be a very suitable agent to repulping if cost were not a factor. The sodium borohydride showed excellent redispersion ability and actually increased the strength properties over the control run, because of its increased ability to swell the fibers. The data did not show any adverse affects on fiber degradation for any of the chemicals or concentrations used.

Recommendations

Some further work in this area could be done to make this process more affordable for companies. Some alternatives that should be looked at are increasing the temperature with steam and repulping at higher temperatures, and decreasing the amount of chemical used. The consistency could also be raised to increase the amount of fiber to fiber contact.

Works Cited

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(2) Merrett, Kym J., "Factors affecting the performance of polyamide type wet strength resins.", APPITA Vol.37, No.3, November 1983, P 233-236.

(3) Burk, John M., " Secondary Fiber with Solvent Dispersant Additives." Southern Pulp and Paper Manufacturer. February 1975. p 22-25.

(4) Westfall, P. M., " Alkaline Curing Wet-Strength Resins." TAPPI Journal, Vol.49, No. 1, June 1966. P56-58.

(5) Eklund, Dan and Tom Lindstrom, "Paper Chemistry", DT Paper Science Publications, Grankulla, Finland, 1991.

APPENDIX 1

Data Tables

Control Run 10 Minutes No Chemical

Sheet Number	Sheet Weight	Grammage (g/m2)				
1	18.70	452.89				
2	18.30	443.20				
3	19.80	479.53				
4	20.30	491.64				
Average	19.28	466.82				
	Tensile Lbf	Tensile Kgf	Tensile Index (N m2/g)			
1	7.96	3.61	5.21			
2	7.37	3.34	4.93			
3	8.05	3.65	4.98			
4	8.75	3.97	5.28			
Average	8.03	3.64	5.10			
	Tear Elm	Tear	Tear	Average	Tear Force	Tear Index (mN m2/g)
1	21.00	24.00	25.00	23.33	3662.40	8.09
2	30.00	25.00	27.00	27.33	4290.24	9.68
3	28.00	24.00	24.00	25.33	3976.32	8.29
4	29.00	32.00	28.00	29.67	4656.48	9.47
Average	27.00	26.25	26.00	26.42	4146.36	8.88
	Burst psi	Burst kpa	Burst index (kPa m2/g)			
1	51.00	351.51	0.78			
2	51.00	351.51	0.79			
3	50.00	344.62	0.72			
4	52.00	358.40	0.73			
Average	51.00	351.51	0.75			

Table 1

Control Run 20 Minutes No Chemical

Sheet Number	Sheet Weight	Grammage (g/m2)				
1	18.50	448.05				
2	17.70	428.67				
3	19.40	469.84				
4	20.40	494.06				
Average	19.00	460.16				
	Tensile Lbf	Tensile Kgf	Tensile Index (N m2/g)			
1	12.80	5.80	8.47			
2	9.10	4.13	6.29			
3	12.80	5.80	8.08			
4	10.40	4.72	6.24			
Average	11.28	5.11	7.27			
	Tear Elm	Tear	Tear	Average	Tear Force	Tear Index (mN m2/g)
1	38.00	41.00	34.00	37.67	5912.16	13.20
2	35.00	36.00	35.00	35.33	5545.92	12.94
3	35.00	34.00	32.00	33.67	5284.32	11.25
4	38.00	35.00	34.00	35.67	5598.24	11.33
Average	36.50	36.50	33.75	35.58	5585.16	12.18
	Burst psi	Burst kpa	Burst index (kPa m2/g)			
1	81.00	558.28	1.25			
2	90.00	620.32	1.45			
3	115.00	792.63	1.69			
4	105.00	723.70	1.46			
Average	97.75	673.73	1.46			

Table 2

Control Run 30 Minutes No Chemical

Sheet Number	Sheet Weight	Grammage (g/m2)
1	19.30	467.42
2	19.50	472.27
3	19.20	465.00
4	20.80	503.75
Average	19.70	477.11

	Tensile Lbf	Tensile Kgf	Tensile Index (N m2/g)
1	19.10	8.66	12.12
2	13.70	6.21	8.60
3	15.80	7.17	10.07
4	19.10	8.66	11.24
Average	16.93	7.68	10.51

	Tear Elm	Tear	Tear	Average	Tear Force	Tear Index (mN m2/g)
1	44.00	38.00	36.00	39.33	6173.76	13.21
2	34.00	36.00	34.00	34.67	5441.28	11.52
3	35.00	34.00	39.00	36.00	5650.56	12.15
4	48.00	41.00	41.00	43.33	6801.60	13.50
Average	40.25	37.25	37.50	38.33	6016.80	12.60

	Burst psi	Burst kpa	Burst index (kPa m2/g)
1	110.00	758.16	1.62
2	118.00	813.30	1.72
3	114.00	785.73	1.69
4	117.00	806.41	1.60
Average	114.75	790.90	1.66

Table 3

1% Sodium Borohydride 10 minutes

Sheet Number	Sheet Weight	Grammage (g/m2)				
1	22.63	548.07				
2	21.22	513.92				
3	23.11	559.70				
4	19.04	461.13				
Average	21.50	520.70				
	Tensile Lbf	Tensile Kgf	Tensile Index (N m2/g)			
1	16.24	7.37	8.79			
2	17.73	8.04	10.23			
3	21.64	9.81	11.46			
4	13.12	5.95	8.44			
Average	17.18	7.79	9.73			
	Tear Elm	Tear	Tear	Average	Tear Force	Tear Index (mN m2/g)
1	55.00	56.00	52.00	54.33	8528.16	15.56
2	28.00	32.00	45.00	35.00	5493.60	10.69
3	46.00	47.00	36.00	43.00	6749.28	12.06
4	30.00	40.00	41.00	37.00	5807.52	12.59
Average	39.75	43.75	43.50	42.33	6644.64	12.73
	Burst psi	Burst kpa	Burst index (kPa m2/g)			
1	169.00	1164.82	2.13			
2	112.50	775.40	1.51			
3	152.10	1048.33	1.87			
4	137.70	949.08	2.06			
Average	142.83	984.41	1.89			

Table 4

1% Sodium Borohydride 20 minutes

Sheet Number	Sheet Weight	Grammage (g/m2)				
1	23.18	561.39				
2	21.10	511.02				
3	19.13	463.30				
4	19.16	464.03				
Average		499.94				
	Tensile Lbf	Tensile Kgf	Tensile Index (N m2/g)			
1	27.07	12.28	14.30			
2	27.18	12.33	15.77			
3	21.70	9.84	13.89			
4	26.71	12.11	17.07			
Average		11.64	15.26			
	Tear Elm	Tear	Tear	Average	Tear Force	Tear Index (mN m2/g)
1	50.00	66.00	60.00	58.67	9208.32	16.40
2	47.00	56.00	50.00	51.00	8004.96	15.66
3	42.00	45.00	44.00	43.67	6853.92	14.79
4	47.00	51.00	50.00	49.33	7743.36	16.69
Average				50.67	7952.64	15.89
	Burst psi	Burst kpa	Burst index (kPa m2/g)			
1	197.60	1361.94	2.43			
2	195.20	1345.40	2.63			
3	182.40	1257.17	2.71			
4	184.50	1271.65	2.74			
Average		1309.04	2.63			

Table 5

1% Sodium Borohydride 30 minutes

Sheet Number	Sheet Weight	Grammage (g/m2)				
1	19.61	474.93				
2	20.31	491.88				
3	20.83	504.48				
4	18.66	451.92				
Average		480.80				
	Tensile Lbf	Tensile Kgf	Tensile Index (N m2/g)			
1	24.54	11.13	15.32			
2	25.62	11.62	15.44			
3	28.60	12.97	16.81			
4	24.59	11.15	16.13			
Average		11.72	15.93			
	Tear Elm	Tear	Tear	Average	Tear Force	Tear Index (mN m2/g)
1	54.00	62.00	47.00	54.33	8528.16	17.96
2	51.00	62.00	49.00	54.00	8475.84	17.23
3	48.00	52.00	55.00	51.67	8109.60	16.08
4	43.00	46.00	42.00	43.67	6853.92	15.17
Average				50.92	7991.88	16.61
	Burst psi	Burst kpa	Burst index (kPa m2/g)			
1	197.60	1361.94	2.87			
2	197.60	1361.94	2.77			
3	193.20	1331.61	2.64			
4	192.40	1326.10	2.93			
Average		1345.40	2.80			

Table 6

3% sodium Borohydride 10 minutes

Sheet Number	Sheet Weight	Grammage (g/m2)
1	21.85	529.18
2	22.71	550.01
3	22.40	542.50
4	23.65	572.77
Average		548.62

	Tensile Lbf	Tensile Kgf	Tensile Index (N m2/g)
1	22.70	10.29	12.72
2	24.17	10.96	13.03
3	20.75	9.41	11.34
4	34.23	15.52	17.72
Average		11.55	13.70

	Tear Elm	Tear	Tear	Average	Tear Force	Tear Index (mN m2/g)
1	57.00	53.00	55.00	55.00	8632.80	16.31
2	67.00	62.00	60.00	63.00	9888.48	17.98
3	66.00	58.00	71.00	65.00	10202.40	18.81
4	56.00	62.00	65.00	61.00	9574.56	16.72
Average				61.00	9574.56	17.45

	Burst psi	Burst kpa	Burst index (kPa m2/g)
1	197.60	1361.94	2.57
2	197.60	1361.94	2.48
3	197.60	1361.94	2.51
4	192.20	1324.72	2.31
Average		1352.63	2.47

Table 7

3% Sodium Borohydride 20 min

Sheet Number	Sheet Weight	Grammage (g/m2)				
1	19.88	481.47				
2	19.11	462.82				
3	19.62	475.17				
4	19.54	473.23				
Average		473.17				
	Tensile Lbf	Tensile Kgf	Tensile Index (N m2/g)			
1	26.83	12.17	16.52			
2	23.21	10.53	14.87			
3	32.80	14.88	20.47			
4	25.88	11.74	16.22			
Average		12.33	17.02			
	Tear Elm	Tear	Tear	Average	Tear Force	Tear Index (mN m2/g)
1	50.00	49.00	51.00	50.00	7848.00	16.30
2	44.00	44.00	53.00	47.00	7377.12	15.94
3	74.00	70.00	75.00	73.00	11458.08	24.11
4	50.00	61.00	55.00	55.33	8685.12	18.35
Average				56.33	8842.08	18.68
	Burst psi	Burst kpa	Burst index (kPa m2/g)			
1	197.50	1361.25	2.83			
2	191.40	1319.21	2.85			
3	171.00	1178.60	2.48			
4	189.00	1302.66	2.75			
Average		1290.43	2.73			

Table 8

3% Sodium Borohydride 30 minutes

Sheet Number	Sheet Weight	Grammage (g/m2)				
1	19.48	471.78				
2	19.63	475.41				
3	19.22	465.48				
4	19.64	475.66				
Average		472.08				
	Tensile Lbf	Tensile Kgf	Tensile Index (N m2/g)			
1	20.86	9.46	13.11			
2	25.65	11.63	16.00			
3	26.50	12.02	16.88			
4	24.94	11.31	15.55			
Average		11.11	15.38			
	Tear Elm	Tear	Tear	Average	Tear Force	Tear Index (mN m2/g)
1	43.00	50.00	45.00	46.00	7220.16	15.30
2	43.00	43.00	45.00	43.67	6853.92	14.42
3	48.00	45.00	41.00	44.67	7010.88	15.06
4	45.00	55.00	47.00	49.00	7691.04	16.17
Average				45.83	7194.00	15.24
	Burst psi	Burst kpa	Burst index (kPa m2/g)			
1	197.50	1361.25	2.89			
2	197.50	1361.25	2.86			
3	190.90	1315.76	2.83			
4	197.50	1361.25	2.86			
Average		1349.88	2.86			

Table 9

1% NaOH 10 minutes

Sheet Number	Sheet Weight	Grammage (g/m2)				
1	19.90	481.95				
2	20.50	496.48				
3	19.00	460.16				
4	21.50	520.70				
Average		489.82				
	Tensile Lbf	Tensile Kgf	Tensile Index (N m2/g)			
1	15.10	6.85	9.29			
2	18.07	8.20	10.79			
3	13.19	5.98	8.50			
4	15.81	7.17	9.00			
Average		7.05	9.40			
	Tear Elm	Tear	Tear	Average	Tear Force	Tear Index (mN m2/g)
1	39.00	38.00	40.00	39.00	6121.44	12.70
2	43.00	46.00	47.00	45.33	7115.52	14.33
3	42.00	40.00	37.00	39.67	6226.08	13.53
4	50.00	46.00	48.00	48.00	7534.08	14.47
Average				43.00	6749.28	13.76
	Burst psi	Burst kpa	Burst index (kPa m2/g)			
1	132.40	912.55	1.89			
2	125.90	867.75	1.75			
3	122.00	840.87	1.83			
4	138.50	954.60	1.83			
Average		893.94	1.83			

Table 10

1% NaOH 20 minutes

Sheet Number	Sheet Weight	Grammage (g/m2)
1	20.10	486.80
2	20.50	496.48
3	20.10	486.80
4	21.10	511.02
Average		495.27

	Tensile Lbf	Tensile Kgf	Tensile Index (N m2/g)
1	22.50	10.20	13.70
2	23.53	10.67	14.05
3	25.48	11.56	15.52
4	24.00	10.88	13.93
Average		10.83	14.30

	Tear Elm	Tear	Tear	Average	Tear Force	Tear Index (mN m2/g)
1	50.00	64.00	49.00	54.33	8528.16	17.52
2	53.00	50.00	53.00	52.00	8161.92	16.44
3	48.00	49.00	45.00	47.33	7429.44	15.26
4	42.00	47.00	48.00	45.67	7167.84	14.03
Average				49.83	7821.84	15.81

	Burst psi	Burst kpa	Burst index (kPa m2/g)
1	191.00	1316.45	2.70
2	195.80	1349.53	2.72
3	178.20	1228.23	2.52
4	179.90	1239.94	2.43
Average		1283.54	2.59

Table 11

1% NaOH 30 minutes

Sheet Number	Sheet Weight	Grammage (g/m2)				
1	20.00	484.38				
2	19.80	479.53				
3	19.80	479.53				
4	20.20	489.22				
Average		483.16				
	Tensile Lbf	Tensile Kgf	Tensile Index (N m2/g)			
1	23.34	10.59	14.29			
2	21.64	9.81	13.38			
3	21.62	9.80	13.37			
4	21.60	9.80	13.09			
Average		10.00	13.53			
	Tear Elm	Tear	Tear	Average	Tear Force	Tear Index (mN m2/g)
1	50.00	48.00	47.00	48.33	7586.40	15.66
2	54.00	52.00	50.00	52.00	8161.92	17.02
3	50.00	51.00	50.00	50.33	7900.32	16.48
4	51.00	54.00	56.00	53.67	8423.52	17.22
Average				51.08	8018.04	16.59
	Burst psi	Burst kpa	Burst index (kPa m2/g)			
1	181.20	1248.90	2.58			
2	197.50	1361.25	2.84			
3	146.10	1006.98	2.10			
4	173.60	1196.52	2.45			
Average		1203.41	2.49			

Table 12

3% NaOH 10 minutes

Sheet Number	Sheet Weight	Grammage (g/m2)
1	19.70	477.11
2	19.90	481.95
3	20.40	494.06
4	20.20	489.22
Average		485.59

	Tensile Lbf	Tensile Kgf	Tensile Index (N m2/g)
1	21.60	9.80	13.42
2	15.10	6.85	9.29
3	20.25	9.18	12.15
4	22.47	10.19	13.62
Average		9.00	12.12

	Tear Elm	Tear	Tear	Average	Tear Force	Tear Index (mN m2/g)
1	50.00	45.00	44.00	46.33	7272.48	15.24
2	52.00	48.00	44.00	48.00	7534.08	15.63
3	45.00	45.00	45.00	45.00	7063.20	14.30
4	43.00	50.00	55.00	49.33	7743.36	15.83
Average				47.17	7403.28	15.25

	Burst psi	Burst kpa	Burst index (kPa m2/g)
1	179.30	1235.81	2.59
2	170.90	1177.91	2.44
3	155.80	1073.84	2.17
4	152.80	1053.16	2.15
Average		1135.18	2.34

Table 13

3% NaOH 20 Minutes

Sheet Number	Sheet Weight	Grammage (g/m2)				
1	18.80	455.31				
2	21.30	515.86				
3	22.00	532.81				
4	20.50	496.48				
Average		500.12				
	Tensile Lbf	Tensile Kgf	Tensile Index (N m2/g)			
1	23.40	10.61	15.24			
2	25.44	11.54	14.62			
3	27.47	12.46	15.29			
4	29.30	13.29	17.50			
Average		11.97	15.66			
	Tear Elm	Tear	Tear	Average	Tear Force	Tear Index (mN m2/g)
1	48.00	50.00	48.00	48.67	7638.72	16.78
2	55.00	42.00	50.00	49.00	7691.04	14.91
3	55.00	45.00	50.00	50.00	7848.00	14.73
4	65.00	50.00	55.00	56.67	8894.40	17.91
Average				51.08	8018.04	16.08
	Burst psi	Burst kpa	Burst index (kPa m2/g)			
1	174.50	1202.72	2.64			
2	197.00	1357.80	2.63			
3	197.50	1361.25	2.55			
4	189.90	1308.87	2.64			
Average		1307.66	2.62			

Table 14

3% NaOH 30 MInutes

Sheet Number	Sheet Weight	Grammage (g/m2)				
1	19.70	477.11				
2	18.90	457.73				
3	19.90	481.95				
4	21.90	530.39				
Average		486.80				
	Tensile Lbf	Tensile Kgf	Tensile Index (N m2/g)			
1	26.09	11.83	16.21			
2	25.97	11.78	16.82			
3	24.34	11.04	14.97			
4	28.44	12.90	15.90			
Average		11.89	15.98			
	Tear Elm	Tear	Tear	Average	Tear Force	Tear Index (mN m2/g)
1	54.00	53.00	51.00	52.67	8266.56	17.33
2	48.00	48.00	48.00	48.00	7534.08	16.46
3	53.00	55.00	54.00	54.00	8475.84	17.59
4	66.00	62.00	65.00	64.33	10097.76	19.04
Average				54.75	8593.56	17.60
	Burst psi	Burst kpa	Burst index (kPa m2/g)			
1	178.60	1230.98	2.58			
2	197.50	1361.25	2.97			
3	197.50	1361.25	2.82			
4	197.50	1361.25	2.57			
Average		1328.68	2.74			

Table 15

1% ClO2 10 minutes

Sheet Number	Sheet Weight	Grammage (g/m2)				
1	21.10	511.02				
2	21.30	515.86				
3	18.30	443.20				
4	18.60	450.47				
Average		480.14				
	Tensile Lbf	Tensile Kgf	Tensile Index (N m2/g)			
1	8.10	3.67	4.70			
2	8.90	4.04	5.12			
3	7.80	3.54	5.22			
4	8.90	4.04	5.86			
Average		3.82	5.22			
	Tear Elm	Tear	Tear	Average	Tear Force	Tear Index (mN m2/g)
1	29.00	30.00	29.00	29.33	4604.16	9.01
2	30.00	30.00	26.00	28.67	4499.52	8.72
3	26.00	24.00	22.00	24.00	3767.04	8.50
4	22.00	26.00	23.00	23.67	3714.72	8.25
Average				26.42	4146.36	8.62
	Burst psi	Burst kpa	Burst index (kPa m2/g)			
1		474.00	0.93			
2		592.00	1.15			
3		392.00	0.88			
4		424.00	0.94			
Average		470.50	0.98			

Table 16

1% ClO_2 20 minutes

Sheet Number	Sheet Weight	Grammage (g/m2)				
1	21.00	508.59				
2	22.00	532.81				
3	20.70	501.33				
4	20.20	489.22				
Average		507.99				
	Tensile Lbf	Tensile Kgf	Tensile Index (N m2/g)			
1	11.99	5.44	6.99			
2	11.05	5.01	6.15			
3	11.90	5.40	7.04			
4	13.30	6.03	8.06			
Average		5.47	7.06			
	Tear Elm	Tear	Tear	Average	Tear Force	Tear Index (mN m2/g)
1	39.00	34.00	33.00	35.33	5545.92	10.90
2	32.00	33.00	33.00	32.67	5127.36	9.62
3	40.00	35.00	37.00	37.33	5859.84	11.69
4	35.00	26.00	34.00	31.67	4970.40	10.16
Average				34.25	5375.88	10.59
	Burst psi	Burst kpa	Burst index (kPa m2/g)			
1		532.00	1.05			
2		558.00	1.05			
3		713.00	1.42			
4		611.00	1.25			
Average		603.50	1.19			

Table 17

1% ClO2 30 minutes

Sheet Number	Sheet Weight	Grammage (g/m2)				
1	20.60	498.91				
2	21.40	518.28				
3	21.40	518.28				
4	21.30	515.86				
Average		512.83				
	Tensile Lbf	Tensile Kgf	Tensile Index (N m2/g)			
1	13.48	6.11	8.01			
2	10.66	4.83	6.10			
3	14.55	6.60	8.32			
4	14.66	6.65	8.43			
Average		6.05	7.72			
	Tear Elm	Tear	Tear	Average	Tear Force	Tear Index (mN m2/g)
1	35.00	36.00	35.00	35.33	5545.92	11.12
2	41.00	38.00	34.00	37.67	5912.16	11.41
3	38.00	48.00	45.00	43.67	6853.92	13.22
4	43.00	43.00	38.00	41.33	6487.68	12.58
Average				39.50	6199.92	12.08
	Burst psi	Burst kpa	Burst index (kPa m2/g)			
1		799.00	1.60			
2		630.00	1.22			
3		768.00	1.48			
4		881.00	1.71			
Average		769.50	1.50			

Table 18

3% ClO2 10 minutes

Sheet Number	Sheet Weight	Grammage (g/m2)				
1	19.20	465.00				
2	19.10	462.58				
3	19.90	481.95				
4	17.10	414.14				
Average		455.92				
	Tensile Lbf	Tensile Kgf	Tensile Index (N m2/g)			
1	7.00	3.17	4.46			
2	4.71	2.13	3.02			
3	9.69	4.39	5.96			
4	8.42	3.82	6.03			
Average		3.38	4.87			
	Tear Elm	Tear	Tear	Average	Tear Force	Tear Index (mN m2/g)
1	25.00	25.00	22.00	24.00	3767.04	8.10
2	24.00	25.00	24.00	24.33	3819.36	8.26
3	30.00	23.00	39.00	30.67	4813.44	9.99
4	26.00	23.00	23.00	24.00	3767.04	9.10
Average				25.75	4041.72	8.86
	Burst psi	Burst kpa	Burst index (kPa m2/g)			
1	50.40	347.38	0.75			
2	58.90	405.96	0.88			
3	65.70	452.83	0.94			
4	49.50	341.17	0.82			
Average		386.84	0.85			

Table 19

3% Chlorine Dioxide 20 minutes

Sheet Number	sheet weight	Grammage (g/m2)				
1	21.60	523.13				
2	19.90	481.95				
3	21.30	515.86				
4	20.70	501.33				
Average		505.57				
	Tensile Lbf	Tensile Kgf	Tensile Index (N m2/g)			
1	13.32	6.04	7.55			
2	7.52	3.41	4.63			
3	14.44	6.55	8.30			
4	12.04	5.46	7.12			
Average		5.37	6.90			
	Tear Elm	Tear	Tear	Average	Tear Force	Tear Index (mN m2/g)
1	40.00	33.00	41.00	38.00	5964.48	11.40
2	36.00	39.00	32.00	35.67	5598.24	11.62
3	39.00	40.00	38.00	39.00	6121.44	11.87
4	32.00	35.00	38.00	35.00	5493.60	10.96
Average				36.92	5794.44	11.46
	Burst psi	Burst kpa	Burst index (kPa m2/g)			
1	99.70	687.17	1.31			
2	105.90	729.91	1.51			
3	103.10	710.61	1.38			
4	90.00	620.32	1.24			
Average		687.00	1.36			

Table 20

3% ClO2 30 Minutes

Sheet Number	Sheet Weight	Grammage (g/m2)
1	20.40	494.06
2	21.00	508.59
3	19.30	467.42
4	22.50	544.92
Average		503.75

	Tensile Lbf	Tensile Kgf	Tensile Index (N m2/g)
1	12.98	5.89	7.79
2	14.53	6.59	8.47
3	10.97	4.98	6.96
4	15.53	7.04	8.45
Average		6.12	7.92

	Tear Elm	Tear	Tear	Average	Tear Force	Tear Index (mN m2/g)
1	39.00	40.00	40.00	39.67	6226.08	12.60
2	33.00	35.00	35.00	34.33	5388.96	10.60
3	36.00	38.00	36.00	36.67	5755.20	12.31
4	49.00	45.00	40.00	44.67	7010.88	12.87
Average				38.83	6095.28	12.09

	Burst psi	Burst kpa	Burst index (kPa m2/g)
1	109.60	755.41	1.53
2	128.50	885.67	1.74
3	78.10	538.30	1.15
4	136.80	942.88	1.73
Average		780.56	1.54

Table 21

Shive Analysis Data

	10 Minutes	20 minutes	30 minutes
Control Run	23.2	4.6	1.6
1% NaBH4	26	1.6	0.9
3% NaBH4	7.13	1.11	0.66
1% NaOH	17.6	3.1	1.8
3% NaOH	8.2	2	0.93
1% ClO2	38.8	29.8	13.4
3% ClO2	42.1	25.8	15.3

Table 22

Fiber Length Analysis

	10 Minutes	20 minutes	30 minutes
Control Run	2.76	2.35	5.69
1% NaBH4	2.94	3.03	3.22
3% NaBH4	3.17	2.75	3.12
1% NaOH	2.53	2.7	2.75
3% NaOH	2.61	2.78	2.75
1% ClO2	2.63	2.71	2.77
3% ClO2	2.42	2.56	2.43

Table 23